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# EVALUATION AND COMPARISON OF SPACE SOLAR POWER CONCEPTS

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## ABSTRACT

The SSP Exploratory Research and Technology (SERT) program undertaken by NASA in the 1999-2000 timeframe was the third in a recent series of NASA sponsored studies of Space Solar Power (SSP) that began with the 1995 SSP "Fresh Look" Study, and was followed by the SSP Concept Definition Study in 1998. In all three studies, a major focus has been on identifying system concepts, architectures and technologies that may ultimately produce a practical, economically viable source of electrical power to help satisfy the world's growing energy needs. As part of the SERT program, members of the study team developed several new and innovative SSP concepts that sprung from a desire to address the problem areas of previous system concepts with new technology and system solutions. In the previous SSP studies it has been shown that systems analyses and sensitivity studies are key to understanding the merits of different system concepts and technologies, particularly with respect to their impact on the mass and cost of space hardware and their ultimate economic impact on the cost of SSP-produced electricity. Enabled by analytical models and tools developed over the series of SSP studies, seven different system concepts as well as different technology choices within these concepts were quantitatively compared with one another on the basis of the mass and cost metrics suggested above. Accompanying sensitivity studies have permitted examination of how variations in the projected capabilities of different technologies could affect conclusions drawn from these analyses. This paper summarizes the results of these analytical efforts and from those results, identifies the most promising SSP concepts, including their key technologies and their comparative advantages and disadvantages.



## INTRODUCTION

The Space Solar Power (SSP) Exploratory Research and Technology (SERT) program was a joint NASA, industry and university effort led by Marshall Space Flight Center (MSFC) with a goal "… to conduct preliminary studies and strategic technology research and development across a wide range of areas to enable the future development of large, potentially multi-megawatt SSP systems and wireless power transmission (WPT) for government missions and commercial markets (in-space and terrestrial)." The SERT program was the third in a series of NASA sponsored studies of space solar power, beginning with the 1995 SSP "Fresh Look" Study, followed by the SSP Concept Definition Study in 1998. In all three studies, a major focus has been on identifying system concepts, architectures and technologies that might ultimately produce a practical, economically viable source of electrical power to help satisfy the world's growing energy needs. This paper documents the results of systems-level modeling and analysis activities performed for the SERT program over its two-year duration.

## SSP CONCEPTS

Three concepts emerged from SERT as the leading microwave-based candidates for SSP implementation. One, the Sun Tower, has evolved from an early concept proposed and examined during the "Fresh Look" study. In its original version (Figure 1), the Sun Tower was a long tower-like configuration, with circular concentrated solar collectors running along its length like petals on a long-stemmed flower. At the bottom of the Sun Tower is a large phased-array microwave transmitter that always faces the Earth as the satellite traverses its orbit. The Sun Tower design called for its deployment in a low altitude Sun-synchronous orbit that assured the solar collectors always faced the Sun. The design was simple, relatively small, low-cost and easily assembled. However, it soon became clear that even with substantial electronic beam-steering, power could be delivered to a given ground station for only minutes a day.

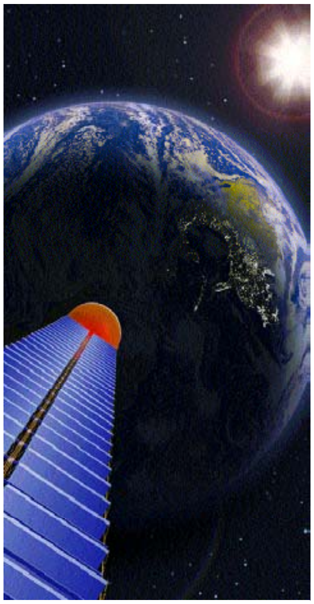

**Figure 1 Sun Tower**

Moving up to Medium Earth Orbit altitudes helped increase the power delivery times to hours rather than minutes, but at the expense of operating in a more difficult radiation environment and with more complex orbital maneuvers. Taking the Sun Tower configuration to Geosynchronous Earth Orbit (GEO), solved many of the problems. Power would be available to a ground site essentially 24 hours a day, the space environment was more benign, and the satellite maneuvers were fairly straight forward; basically just requiring one full rotation of the solar arrays every 24 hours. However, due to the Sun Tower's orientation in its orbit, each day the solar arrays would go from full solar illumination to full or partial shadowing, caused either by the Earth or by the arrays themselves. Furthermore, the orbit's high altitude required the satellite's transmitter to grow substantially in size to overcome the natural spreading of the power beam as it traveled the larger distance to Earth. In addition to the much larger transmitter, efficient operation in GEO also requires much greater power levels. Unfortunately, because of its unique configuration the Sun Tower is able to grow in only one dimension and consequently the result was extremely long, heavy electrical cabling running tens of kilometers in length.

A Solar Power Satellite can avoid the varying illumination problem encountered by the Sun Tower in GEO by employing an orbital configuration that allows the satellite to maintain its solar arrays pointed at the sun while letting it's transmitter array slowly rotate so that it is always facing the Earth. This was the design approach taken by the early Solar Power Satellite study performed in the 1970's. Unfortunately, this approach requires an enormous amount of electrical power to be passed through a massive rotating joint via slip rings, which represents a single failure point for the whole system in this one, non-replaceable unit.

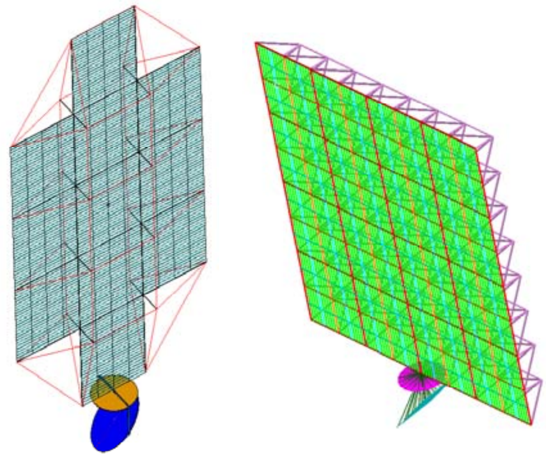

**Figure 2 Abacus Reflector configurations**

More recent concepts developed during the course of our current studies would either replace that single rotating joint with a large number of smaller slip rings, or keep the transmitter stationary and use a large rotating reflector to redirect the microwave energy to Earth. This latter concept has been named the Abacus Reflector (Figure 2) due to the appearance of its two-dimensional solar array structure.

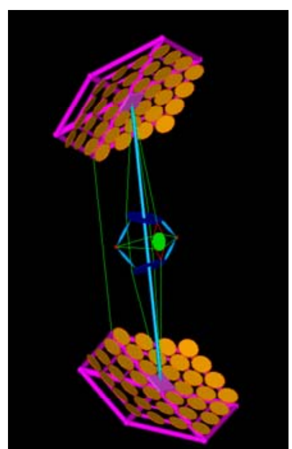

**Figure 3 ISC**

While the added array dimension reduces the electrical cable lengths over those in the Sun Tower design, the weight of these cables along with the required voltage conversion and other power management equipment still forms a significant fraction of the total satellite mass. With this in mind, another concept was proposed that would substantially reduce power management and distribution mass. This concept, called the Integrated Symmetrical Concentrator (Figure 3) or ISC for short, would redirect the Sun's energy by reflection, rather than first converting it to electricity and then distributing it over long cable lines. The concept is based on an unusual structural configuration consisting of two symmetrical clusters of very large, flat solar reflectors, arranged so that they reflect and concentrate the Sun's energy on another structure consisting of two solar arrays surrounding a central transmitter. This second structure would then rotate so that the transmitter continuously points to the Earth while the solar reflectors always face the Sun.

## ANALYSIS TOOLS

Since the "Fresh Look" study, two computer models have been used exclusively by NASA to analyze the technical and economic performance of proposed SSP system concepts. These two analytical tools, the Space Segment Model (SSM) developed by Science Applications International Corporation (SAIC), and the Integrated Architecture Assessment Model (IAAM) developed by Futron Corporation, were both created as part of the "Fresh Look" study and refined during the course of the CDS and SERT studies that followed.

Both models were developed concurrently and were designed to work seamlessly with one another. However, SSM was designed primarily as an independent tool for estimating the mass, performance and cost of solar power satellites (SPS) as well as other space and ground-based assets. As a tool, SSM is usually run separately from IAAM, and allows its users to vary the configuration, size, technology alternatives, orbits and a multitude of other system design options to determine their impact. It also allows the user to evaluate sensitivities, uncover system design issues, identify technology needs, and to perform design optimization.

When used in conjunction with IAAM, selected outputs from SSM are used to effectively characterize what IAAM refers to as the "Space Segment" of an SSP Architecture. For the purposes of IAAM, the Space Segment is basically the full complement of solar power satellites, arranged in selected orbital slots, covering one or more orbits as defined by the architecture.

The Space Segment is but one of several system elements that IAAM uses in its representation of a complete SSP architecture. Other IAAM elements include, Ground Launch Infrastructure, ETO System, In-Space Transportation, In-Space Infrastructure, SSP Ground Segment, SSP Manufacturing, and Commercial Power Utilities Interface. Through modeling performance-related cost factors associated with these elements, IAAM provides a comprehensive accounting of all costs incurred in the development, manufacture, deployment and operation of a complete SSP architecture, including costs associated with investment and financing. IAAM then integrates these costs with projections of potential market demand, pricing, and revenues, to enable systematic and quantitative assessments of economic feasibility of proposed SSP systems and architectures under various user-defined scenarios.

## ANALYSIS PROCESS

Systems analyses and sensitivity studies are key to understanding the merits of different system concepts and technologies with respect to their impact on the mass and cost of space hardware and their ultimate economic impact on the cost of SSP-produced electricity. Through such analyses, using analytical models like SSM and IAAM, different system concepts as well different technology choices within these concepts can be quantitatively compared with one another on the basis of the mass and cost metrics suggested above. Furthermore, accompanying sensitivity studies permit examination of how variations in the projected capabilities of different technologies could affect conclusions drawn from these analyses.

Analysis and comparison of the wide range of SSP system concepts, technologies and performance parameters embraced by the SERT program required the development of a systematic process that would avoid the need to perform an exhaustive investigation of all possible combinations of available options. However, the analysis process had to be sufficiently comprehensive to ensure fair representation of all critical technologies and infrastructure elements.

### Systems

The process ultimately developed to carry out the analyses starts with seven SSP system concepts based on variations of the three basic concepts identified during SERT as primary candidates. They are:

1. Basic Sun Tower with Rotating (Sun-Tracking) Arrays
2. Basic Sun Tower with Stationary (Two-Sided) Arrays
3. Abacus Sun Tower with Rotating (Sun-Tracking) Arrays
4. Abacus Sun Tower with Stationary (Two-Sided) Arrays
5. Abacus Reflector

6. Integrated Symmetrical Concentrator (ISC) High Concentration Ratio
7. Integrated Symmetrical Concentrator (ISC) Low Concentration Ratio

The first four candidates are gravity-gradient concepts, oriented with their transmitter always nadir-pointing towards the Earth. The remaining three candidates are perpendicular-to-the-orbit plane (POP) concepts, oriented so that as they orbit the Earth, their solar collectors always face the Sun and their transmitter rotates to face the Earth. The plan was to start with these seven concepts, outfit each of them with technology options that minimize their mass and/or cost, and compare them with one another in order to down-select the "best" configuration in each of the following three categories:

1. Gravity Gradient
2. Abacus Reflector
3. ISC

These three concept categories were selected because each has their own unique benefits and problems. For example, gravity gradient concepts are possibly the easiest to assemble and control, however the energy they can deliver each orbit is limited either by self-shadowing of rotating arrays or cosine losses in fixed arrays. The power they deliver consequently varies over the day, and for baseload power markets, must be compensated by substantial energy storage or an auxiliary power source at the ground station.

Such drastic measures are not required for the Abacus Reflector which, like the ISC and other POP concepts, delivers a continuous level of power (with the exception of short eclipse periods twice a year) and needs much less ground energy storage. The Abacus Reflector design is also highly modular which has benefits for its packaging, assembly and maintenance. However, attitude control and the extreme surface accuracy requirement for the RF reflector are major concerns. The Abacus Reflector category is represented by only one concept, since a dual reflector concept was rejected early in the study.

ISC, with its unique structural design, represents the third concept category, and comes in two versions. One version is designed for a high concentration ratio (~4:1) and offers the potential of being the lightest weight, lowest cost configuration of all the candidates. However, in addition to attitude control concerns similar to the Abacus Reflector, the expected temperatures at the ISC solar arrays presents a significant problem for conventional array technologies and thermal control techniques. A second version of ISC uses a lower concentration ratio (~2:1) design to overcome the thermal problem, but is much heavier.

Technologies

The next step in the process was to select the technologies to be used in analyzing the seven candidate concepts. Based on an initial evaluation of their overall impact on flight system mass and cost, the most critical SSP technologies were determined to be Solar Power Generation (SPG), Power Management and Distribution (PMAD), and Wireless Power Transmission (WPT). Another critical technology was found to be low-thrust propulsion, but since its effect on the performance of a particular configuration is second-order at best (primarily its relationship to configuration packaging and number of payloads to be delivered to GEO) propulsion technology was not considered in the configuration down-selection process.

**Table 1 Selected Technology Options**

| **Solar Power Gen (SPG) Options** | **Code** |
|---|---|
| Stretched Lens Array (SLA) | S |
| Rainbow Array | R |
| Thin Film PV | T |
| Quantum Dot | Q |
| Brayton Cycle Solar Dynamic (SD) | B |
| **PMAD Options** | **Code** |
| DC-DC Conversion | D |
| DC-AC-DC Conversion | A |
| LT Superconductor | L |
| HT Supercondutor | H |
| **WPT Options** | **Code** |
| Solid State (GaN) | SS |
| Magnetron | M |
| Klystron | K |

The technologies selected as options for different configurations are shown in Table 1. For SPG, the five selected technologies were deemed the most promising based on the long-term projections of their performance provided by GRC and JPL technologists. For PMAD, the primary option for power bus cabling and voltage conversion was simply the choice of DC or AC. Data for the superconductor options shown in the table were not available in time for the configuration down-select, and those options were left for evaluation at a later date. Lastly, the technology options for WPT are represented by the three RF transmitter devices that have been carried as options throughout the SSP study. Note that letter codes have been assigned to each option so that when used in combination for a particular configuration, they can be easily identified through a nomenclature which parenthetically adds them to the configuration name. For example, Sun Tower (M,T,D) refers to a Sun Tower configuration with a Magnetron transmitter, Thin film arrays, and a DC bus, and ISC (SS,Q,A) refers to an ISC configuration with a Solid State transmitter, Quantum dot arrays, and an AC bus.

Configuration/Technology Compatibility

Because some of the SPG technology options are not compatible with certain concepts, the number of configurations to be evaluated and compared can be reduced significantly. The solar pointing requirements of SPG options employing concentrators, such as SLA, Rainbow, and Brayton make them incompatible with gravity gradient concepts that use fixed arrays. In fact the pointing accuracy required by Brayton cycle SD systems makes their compatibility with rotating array gravity gradient systems also questionable.

Pointing requirements also prevent the SPG concentrator options from taking full advantage of the solar concentration provided by the reflectors in the ISC concepts. Furthermore, regardless of whether or not they employ concentrators, most PV arrays including Thin Film are incompatible with the high concentration version of ISC because of temperature concerns. Based on information provided by GRC, the only array technology capable of efficient operation at the high temperatures imposed by the High Concentration Ratio ISC concept is Quantum Dot. However its state of technology readiness at this time prevents it from competing as a practical SPG option for the other concepts.

The Abacus Reflector configuration is basically compatible with all the SPG technologies. The exclusion of Quantum Dot arrays from its trade space was based strictly on its low Technology Readiness Level (TRL).

## CONFIGURATION COMPARISONS

Evaluation of the full set of system configurations with respect to launched Initial Mass in LEO (IMLEO) and recurring cost yielded the results shown in Figures 4 and 5.

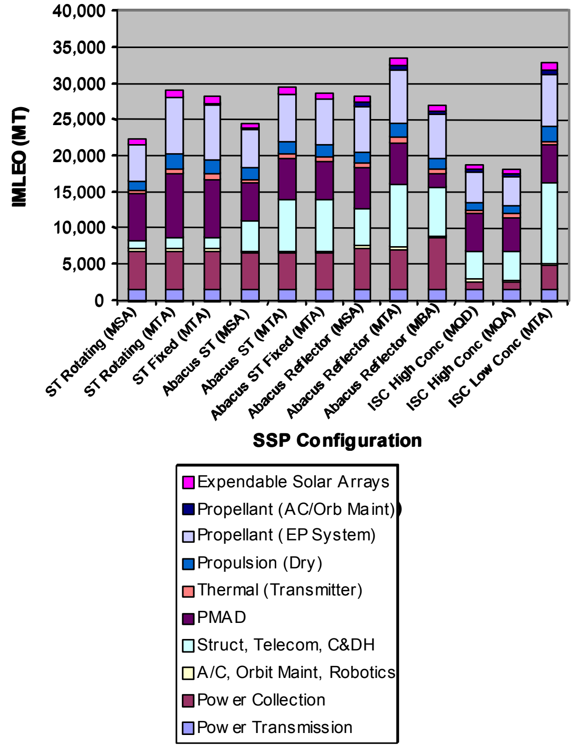


**Figure 4 Mass Comparisons**

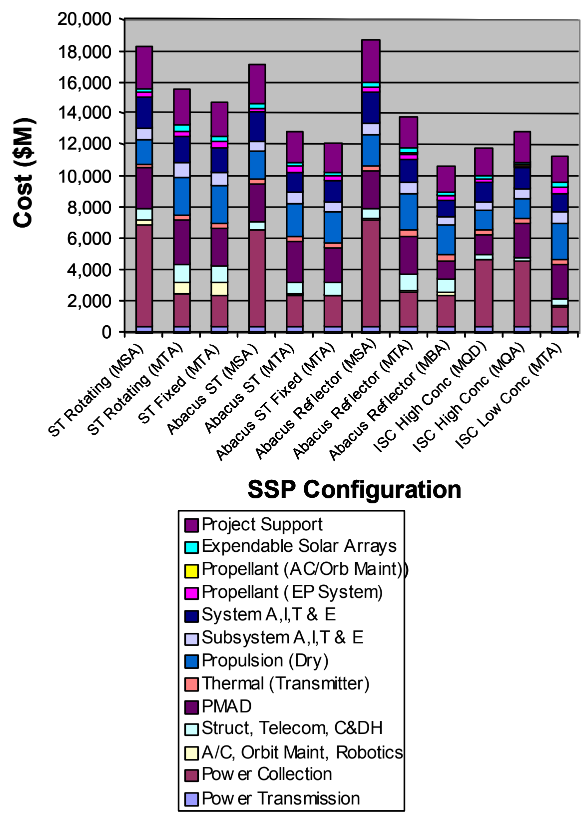


**Figure 5 Cost Comparisons**

Note that both the minimum mass and minimum cost configurations for each concept are shown in these bar charts. Also, each bar indicates the various system components that contribute to the mass/cost totals for a particular configuration.

Because a configuration that minimizes the mass of a system concept is not necessarily the configuration that minimizes its cost, it is most likely that a concept would be represented by two configurations in these charts. This is shown to be true for the rotating array versions of the Sun Tower and Abacus Sun Tower as well as the for the High Concentration Ratio ISC concept. However, concepts where only one array option was considered, as in the fixed array versions of the Sun Tower and the Low Concentration Ratio ISC, could each be represented by a single configuration that produced both minimum mass and cost. The Abacus Reflector concept turned out to be a special case. Configurations employing the Brayton SD option appeared to have an advantage in both mass and cost over any array option. But because the performance projections for Brayton technology that were used in the analyses require far greater technology advancement than the PV arrays, it was felt prudent to also carry along the best PV option. Since one PV option had mass advantage over the others and a second PV option had a cost advantage, the Abacus Reflector wound up being represented by three configurations.

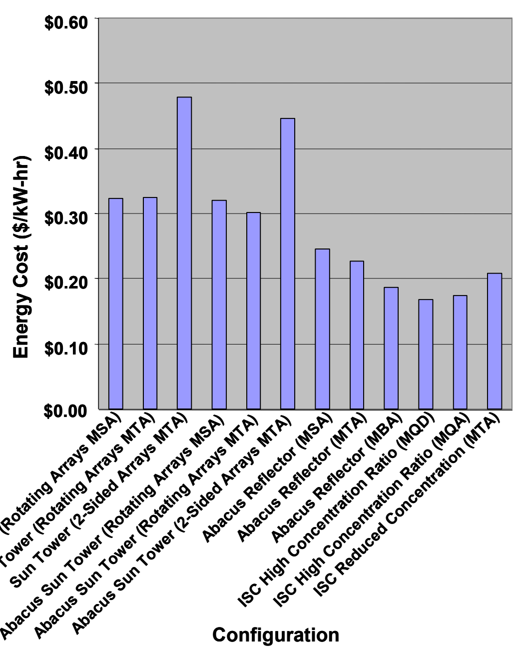


**Figure 6 Energy Cost by Configuration**

By running comparisons of the ultimate energy costs which factors in both the mass and cost of the space system along with ground segment, launch and in-space transportation costs, the number of candidate configurations could be reduced still further. Figure 6 shows such a comparison based on the economic assumptions given in Table 2. In Figure 6 it is clear that from an energy cost viewpoint, the best Gravity Gradient configuration is the Abacus Sun Tower equipped with magnetrons, thin film rotating arrays, and AC power technology. But except for the fixed array concepts, which were clearly not competitive, the energy cost differences among the Gravity Gradient configurations were very small. Since the energy cost performance of the conventional Sun Tower with rotating arrays is very close to similarly equipped Abacus Sun Tower configurations, it was felt that there was also no need to include both concepts in the in the sensitivity studies to follow, and that either concept would be representative of the other. Consequently the Rotating Array Abacus Sun Tower (MTA) was selected. However, the cost difference between that configuration and one using stretched lens arrays is small enough so that is was decided that the SLA option should be carried as well.

All three Abacus Reflector configurations were retained for further analysis, primarily to determine their sensitivity to SPG performance. Based on energy cost and mass performance the Low Concentration Ratio ISC concept was dropped in favor of the two High Concentration Ratio ISC configurations. The two selected ISC configurations differed only in that one used DC current for its PMAD technology while the other used AC.

**Table 2 Economic Assumptions**

| | |
|---|---|
| Economic life (period for equity financing) | 12 |
| Years of debt financing | 20 |
| Return on equity | 15% |
| Cost of capital | 8% |
| Equity Financed | 30% |
| Debt Financed | 70% |
| Years of SSP operations | 40 |
| Years to disperse funds | 2 |
| Cost Contingency | 0% |
| ETO Transportation Cost ($/kg) | 400 |
| In-Space Transportation Cost ($/kg) | 400 |

In summary, after a SSM-enabled comparison of the mass and costs associated with a broad range of different SSP configurations combining concepts and technologies, seven different flight system configurations were selected to continue into the sensitivity study phase of the analysis process. The selected configurations are:

1. Abacus Sun Tower, Rotating Arrays (MTA)
2. Abacus Sun Tower, Rotating Arrays (MSA)
3. Abacus Reflector (MBA)
4. Abacus Reflector (MTA)
5. Abacus Reflector (MSA)
6. ISC High Concentration Ratio (MQD)
7. ISC High Concentration Ratio (MQA)

Based on "most likely" projections of technology performance in the 2025 timeframe the following conclusions can be drawn with respect to technology preferences for the different configurations. In all cases Magnetrons (M) showed advantages over Klystrons (K) and Solid State (SS) transmitter devices. Thin film (T) and Stretched Lens (S) arrays provided better performance than Rainbow (R) arrays for those configurations that could accept them. However, Brayton (B) Solar Dynamic systems appear to be an even better SPG technology for Abacus Reflector concepts if their performance projections hold true. Quantum Dot (Q) technology was needed to withstand the temperatures produced in the High Concentration ISC concepts, but its low Technology Readiness Level make it a riskier option for other concepts. Lastly, AC (A) power appears to be preferable to DC (D) power in almost all cases, with DC competitive only for the shorter cable runs required by the ISC concepts.

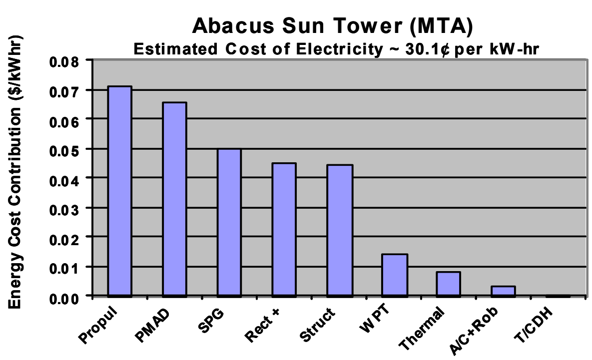


**Figure 7a Technology Contributions to Energy Costs for MTA Abacus Sun Tower**

## SENSITIVITY STUDIES

Only a selected subset of all the many possible sensitivity studies are presented below. These were selected to highlight the most important technology trades. The relative importance of each technology to a particular system configuration can perhaps best be related to the contribution each makes to the cost of energy produced by that system. Figures 7a to 7d provide this information for four different configurations: the Abacus Sun Tower (MTA), the Abacus Reflector (MTA), the Abacus Reflector (MBA) and the ISC High Concentration Ratio (MQD).

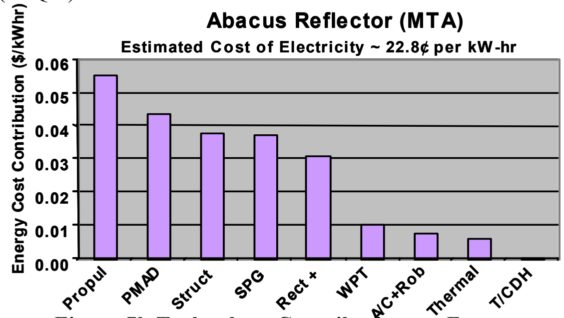


**Figure 7b Technology Contributions to Energy Costs for MTA Abacus Reflector**

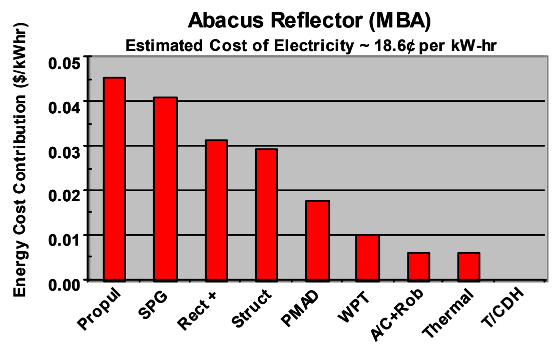


**Figure 7c Technology Contributions to Energy Costs for MTA Abacus Reflector**

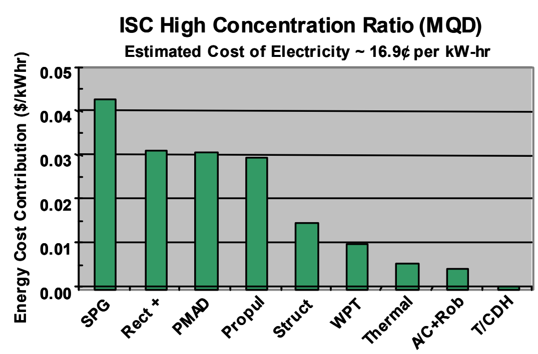


**Figure 7d Technology Contributions to Energy Cost s for MQD High Concentration ISC**

In the four bar charts that comprise this figure, the contributions of the various technologies and/or subsystems to the computed energy cost of each configuration are presented in decreasing order of importance along the x-axes.

ETO and Space Transportation

Earth to Orbit (ETO) launch costs are not explicitly indicated as a contributor to the configuration energy costs in Figure 7, however its contribution based on $400/kg of launched mass, is included as part of the cost of every subsystem cost with the exception of the Rectenna and Ground System. The sensitivity of the resultant cost of electricity to launch pricing is shown in Figure 8 for each configuration. It is also seen that different configurations have different sensitivities to ETO cost. As expected, most of the difference in these sensitivities can be directly related to mass. For the heavier configurations such as those using thin film or Brayton arrays, launch costs represent a greater percentage of the energy cost than they do in lighter systems. Therefore these configurations are naturally more sensitive to variations in launch pricing. Another factor that adds to their greater sensitivity is the fact that these heavier configurations require larger initial investments for the launch services needed to deploy them. This results in additional investment expenses that contribute to the cost of electricity produced by the system, and also increase the sensitivity to launch cost.

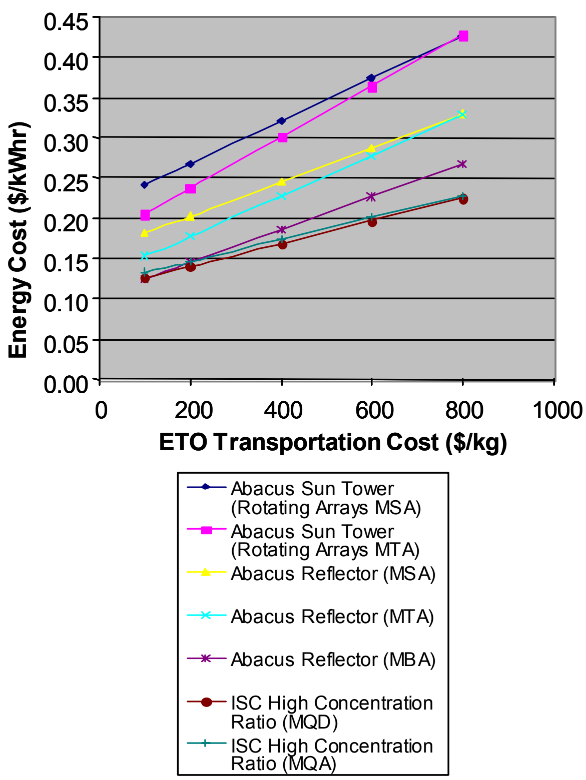


**Figure 8 Energy Cost Sensitivity to ETO Costs, Assuming Self-Transfer (SEP) to GEO**

The results shown in Figure 8 assume that individual payloads launched to LEO, would have the capability of transporting themselves to their GEO assembly point at no additional cost. The basis for this assumption is a scenario wherein a complete Solar Electric Propulsion (SEP) system, including propellant, would be launched as part of each ETO payload. The payload would then essentially transport itself to GEO using the SEP system, which upon assembly would then be used for attitude control and station-keeping. A second option would be to purchase the LEO to GEO space transportation services at an agreed price per kilogram, just as launch services are purchased. Figure 9 presents the energy cost sensitivities to this space transportation price, starting from a baseline estimate of $400/kg.

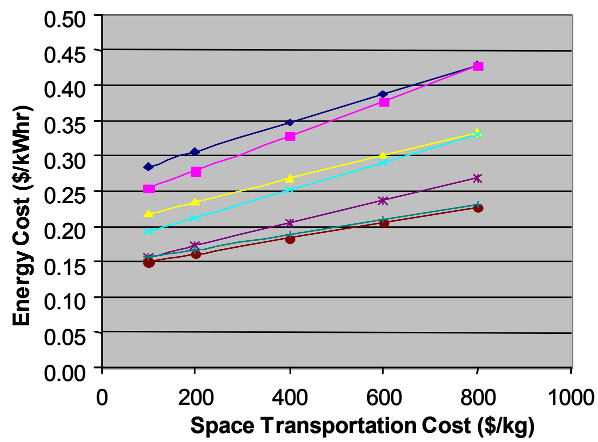


**Figure 9 Energy Cost Sensitivity to Space Transportation Cost, Assuming $400/kg for ETO**

In computing the sensitivities shown in Figure 9, no propulsion subsystem or propellant (with the exception of Attitude Control) was included in the configuration mass estimates and the ETO launch costs were fixed at $400/kg. It is then interesting to note that for all configurations, the additional $400/kg space transportation cost leads to slightly higher energy cost by about 1 to 3 cents a kilowatt-hour. To achieve the same energy costs as the self-transport option, Figure 9 shows that the space transportation costs should not exceed $300/kg.

<u>Propulsion</u>

In Figure 7, the propulsion subsystem appears to be a leading contributor to the energy cost for most configurations. This subsystem appears only in the self-transport option discussed above, and consists of the Solar Electric Propulsion (SEP) system used to transfer the satellite payloads from LEO to GEO, including its propellant and tankage, as well as auxiliary solar arrays to provide power needed by the SEP. The arrays are considered expendable since their useful lifetime would be limited by the slow passage through the Earth's radiation belts.

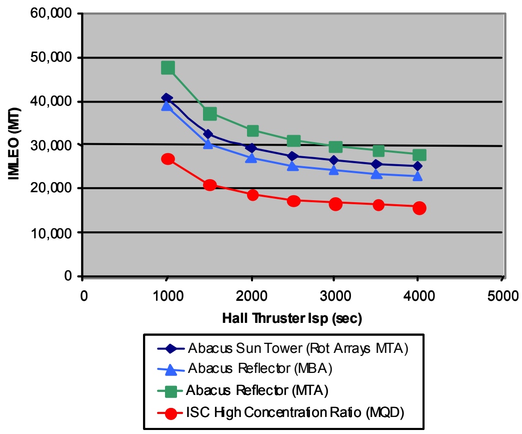


**Figure 10a Configuration Mass Sensitivity to Thruster Isp**

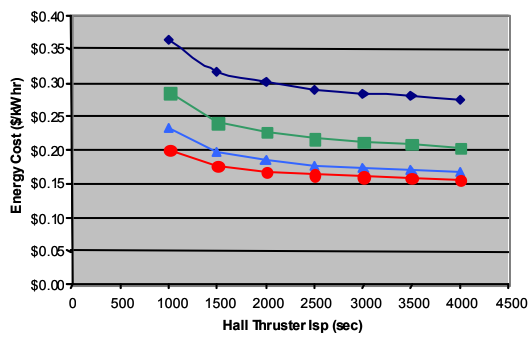


**Figure 10b Energy Cost Sensitivity to Thruster Isp**

Because the propellant used for the LEO to GEO transfer represents such a large fraction of the launched mass of each system configuration, technology advancements that increase propulsion system specific impulse, Isp, should result in less propellant and tankage mass and reduced launch costs. Therefore a sensitivity analysis relating configuration mass and energy cost to the Isp of a propulsion system employing Hall thrusters was performed. The results are shown in Figures 10a and 10b. The sensitivities displayed indicate substantial benefits in both mass and energy cost of having a propulsion Isp of at least 2000 seconds (the baseline value used for these systems), but also show that further increases in Isp have far less impact.

<u>Solar Power Generation</u>

Another big contributor to SSP energy cost is Solar Power Generation. As can be seen from Figures 4 and 5, power collection accounts for a large part of the mass and perhaps the largest part of the cost for most of the SSP configurations. Of these configurations, the Abacus Reflector concepts have the greatest number of SPG options available to them and, as a sensitivity study, it is informative to examine how advancements in these SPG technologies can affect the mass and cost performance of these concepts.

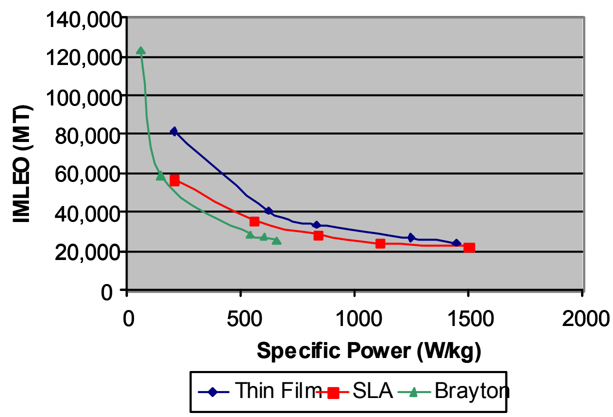


**Figure 11a Abacus Reflector Mass Sensitivity to Specific Power**

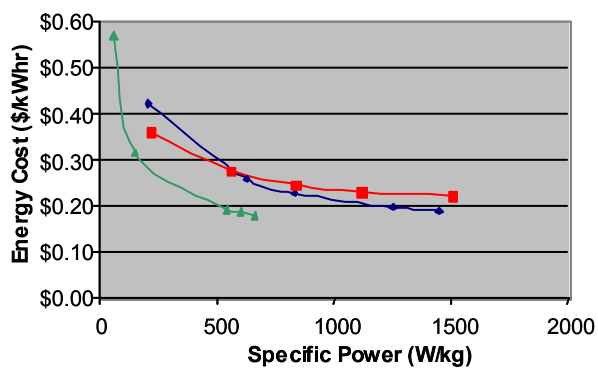


**Figure 11b Abacus Reflector Energy Cost Sensitivity to Specific Power**

Figures 11a and 11b displays the sensitivity of Abacus Reflector configurations to the specific power, i.e. W/kg, of three of their most capable SPG technology options – Thin Film, SLA, and Brayton. The three sensitivity curves start at the specific power values (at the array level) that are reported to be available in current or near term versions of SPG systems using the different technologies. The dramatic reductions in both mass and energy cost as specific power values of the respective SPG systems are increased through technology advancements to their long term projections (approximately 830 W/kg for both PV systems and 600 W/kg for the Brayton arrays) and beyond are clearly evident in the graph.

Of the three SPG options shown in the figure, Brayton potentially offers the most significant performance improvement from its current state, if the projections for specific power can be truly realized through the anticipated advancements in technology. However, since the performance offered by its current technology suffers greatly in comparison to the two PV options, Brayton may be viewed as a riskier choice.

With respect to the two PV options, it is interesting to note the crossover in their curves for energy cost sensitivity, which occurs at a specific power of about 500 W/kg. At lower values of specific power, the energy cost for SLA-based configurations is less than those using thin film and at higher specific powers, thin film has the advantage. The reason for this is that, because of their solar concentrators and higher efficiency, SLA arrays are inherently smaller and lighter than thin film arrays. Therefore at lower values of specific power, the lower cost of launching the lighter SLA configurations more than compensates for its higher cost per Watt. As specific powers increase for both PV systems, and both arrays become lighter, the situation is reversed.

PMAD Voltage Conversion

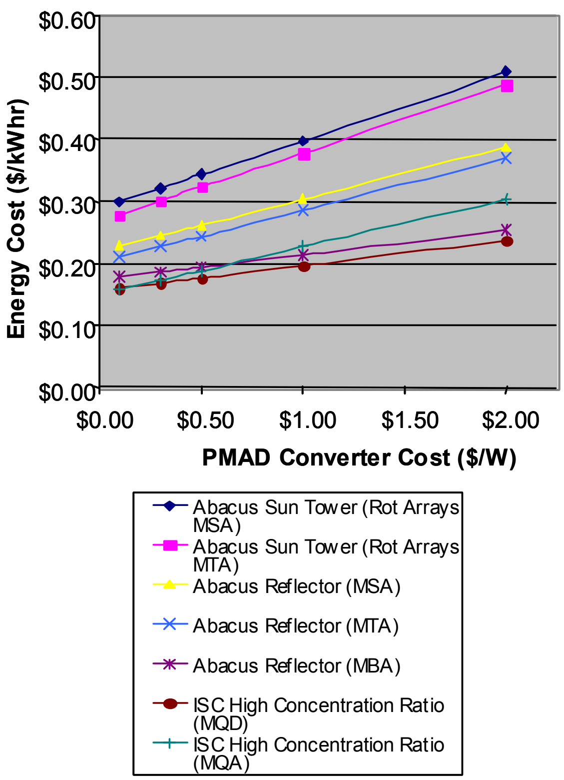


**Figure 12 Energy Cost Sensitivity to PMAD Converter Cost**

Another large contribution to energy cost comes from the PMAD subsystem and the voltage converters in particular. In terrestrial applications the mass of these components is essentially irrelevant and their pricing is directly related to their power handling capability. Current prices of terrestrial converters run about $0.20 per Watt. Mass and reliability have, of course, greater importance in space applications and converter prices can range over two orders of magnitude more than their terrestrial counterparts. Because this wide range of prices presents a substantial cost uncertainty for an essential component, it was felt that the impact of this uncertainty can be best expressed in terms of its effect on the cost of energy produced by each configuration. These sensitivities are shown in Figure 12. Since the sensitivity curves are basically linear, it was not necessary to extend the range of converter costs over two orders of magnitude to observe the effect on energy cost. In essence, the curves show two basic slopes depending on whether a configuration requires converters at both the arrays and the transmitter, or only at the transmitter . The latter case applies to the Abacus Reflector with Brayton arrays and the ISC configuration using DC power. All of the other candidate configurations require two sets of converters. However, even over the "limited" range of converter costs, the sensitivity curves indicate that their effect on the cost of energy is almost as significant as the cost per kilogram charged for ETO launch.

Based on far-term projections provided by James Dolce of NASA GRC, a converter cost of $0.30 per Watt was used as the baseline in SSM. This is a 50% increase over the cost of current terrestrial units and was felt to be adequate to cover the additional cost of design modifications needed to accommodate the mass and volume constraints imposed by space applications, and to cover additional processing to allow them to be space qualified for operation in this new environment which would include concerns over out-gassing, coronal discharge, etc.

Other Sensitivities

Space doesn't allow a full discussion of the other sensitivity analyses performed as part of the SERT study. The analyses addressed sensitivity to WPT technology, the rectenna/ground system, delivered power, and production learning improvement rate. Detailed discussion of these analyses can be found in the SERT Systems Integration and Modeling Report.

## SUMMARY AND CONCLUSIONS

The systems integration activities conducted under the SERT program have identified several new configurations that eliminate the large power-conducting slip rings that were so problematic in previous SSP concepts that operated in POP attitudes similar to the 79 Reference Concept. These new configurations include the Abacus Reflector (both single and double reflector versions), the Integrated Symmetrical Concentrator (both high and low concentration versions), and the Halo concept (developed and studied by the Aerospace Corporation). The Sun Tower derived gravity gradient concepts, including the new Abacus configurations, also have no large power conducting slip rings (the rotating array versions of these concepts do have slip rings but they are not large and do not represent single failure points). An emphasis on minimum PMAD configurations, motivated by the large cabling and converter masses in most of the configurations of previous SSP studies, led to the ISC and Halo concepts so they also possess this additional attribute.

Although it has not been discussed in this paper, work done by Boeing, Aerospace and University of Alabama Huntsville as part of their SERT activities, have led to some very promising distributed laser configurations based on the Sun Tower concept and also on smaller, independent spacecraft in Halo orbit constellations at GEO.

Based on the modeling and analysis activities conducted by the systems integration team, it was determined that the most promising RF configurations to date are:

- ISC, which represents the lightest, most cost-effective concept, but which requires advanced PV (Quantum Dot) or thermal management technology.
- Abacus Reflector, which provides a highly modular design for easier assembly and maintenance, and lower energy cost than gravity gradient concepts, but whose reflector poses design issues and a potentially large loss in efficiency.
- Sun Tower including the Abacus Sun Tower is the easiest configuration to assemble and control, but produces the highest energy cost due to shadowing of the arrays during its orbit.

Other observations derived from the SERT systems analyses suggest that:

- Orbit transfer propulsion, solar power generation, PMAD and ground systems are the primary contributors to SSP delivered energy costs.
- SSP system size and cost are most sensitive to WPT and SPG efficiencies.
- Configurations delivering 1.2GW have an energy cost range of 17¢-32¢/kWhr, which can be reduced by approximately 1¢ to 2 ¢/kWhr by delivering higher power densities per satellite
- Under current pricing assumptions, self-transfer of SSP payloads from LEO to GEO is more cost-effective than a purchased space transportation service
- Advanced technology SEP systems offer an excellent non-nuclear transportation alternative for HEDS missions to the Moon and Mars.

Conclusions that can be drawn from the larger SERT systems integration studies of Space Solar Power, include the following:

- SSP technology can enable near-term space exploration and development.
- Advancements in SSP-related technologies produce wide-ranging performance and cost benefits for commercial, scientific and exploratory space applications.
- Microwave SSP systems are relatively efficient, and can beam power through clouds and light rain
- RF spectral constraints on SSP side-lobes and grating-lobes imposed by the ITU result in design and filtering requirements that lead to reduced efficiency and larger, more costly systems.
- Laser SSP systems allow smooth transition from conventional power to SSP, offer more useful space applications, and open up new architecture options
- Laser and microwave SSP systems may have differing design drivers, and because of their potential, laser based systems deserve comparable consideration in future studies.
- Significant advances in reducing the cost and increasing the launch rates for both ETO and in-space transportation are necessary to realize the potential of Space Solar Power
- To deliver cost-effective power from space, manufacturing and testing processes for space systems must become more efficient and capable

of managing huge volumes, and further provide significant high production cost improvements.

## REFERENCES


1. Feingold, H. et. al., *Space Solar Power: A Fresh Look at the Feasibility of Generating Solar Power in Space for Use on Earth*, Report No. SAIC-97/1005, Contract No. NAS3-26565, Task Order 9, Science Applications International Corporation, April 4, 1997.

2. Feingold, H. et. al., *Space Solar Power: 1998 Concept Definition Study,* Report No. SAIC-99/1016, Contract No. NAS3-26565, Task Order 19, Science Applications International Corporation, February 1999.

3. Feingold, H. et. al., *SERT Systems, Integration, Analysis and Modeling,* Report No. SAIC-01/1045, NASA MSFC Purchase Order No. H-32458D, June 2001